FUEL INJECTOR DRIVER CIRCUIT WITH ENERGY STORAGE APPARATUS

By:

Michael J. French
Eric A. Criteser

EXPRESS MAIL MAILING LABEL
NUMBER: EL 432 943 280 US
DATE OF DEPOSIT: August 18, 2000

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5 ## BACKGROUND OF THE INVENTION

1. Field Of The Invention

The present invention relates generally to an apparatus and method for delivering fuel for combustion in an internal combustion engine. More specifically, the present

10 invention relates to an apparatus and method for increasing the speed of a fuel injector by using a capacitor to store energy which can be used to accelerate the rate at which an electro-mechanical solenoid returns to its initial position.

2. Description Of The Related Art

15 A wide range of pumps have been developed for displacing fluids under pressure produced by electrical drives. For example, in certain fuel injection systems, fuel is displaced via a reciprocating pump assembly which is driven by electric current supplied from a source, typically a vehicle electrical system. In one fuel pump design of this type, a reluctance gap coil is positioned in a solenoid housing, and an armature is mounted

20 movably within the housing and secured to a guide tube. The solenoid coil may be energized to force displacement of the armature toward the reluctance gap in a magnetic circuit defined around the solenoid coil. The guide tube moves with the armature, entering and withdrawing from a pump section. By reciprocal movement of the guide tube into and out of the pump section, fluid is drawn into the pump section and expressed from the pump

25 section during operation.

In pumps of the type described above, the armature and guide tube are typically returned to their original position under the influence of one or more biasing springs.

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Where a fuel injection nozzle is connected to the pump, an additional biasing spring may be used to return the injection nozzle to its original position. Upon interruption of energizing current to the coil, the combination of biasing springs then forces the entire movable assembly to its original position. The cycle time of the resulting device is the sum of the time required for the pressurization stroke during energization of the solenoid coil, and the time required for returning the armature and guide to the original position for the next pressure stroke. Engine speed is generally a function of the flow rate of fuel to the combustion chamber. Increasing the speed of the engine shortens the duration of each combustion cycle. Thus, a fuel delivery system must provide the desired volumes of fuel for each combustion cycle at increasingly faster rates if the engine speed is to be increased.

Where such pumps are employed in demanding applications, such as for supplying fuel to combustion chambers of an internal combustion engine, cycle times can be extremely rapid. Cycle time refers to the amount of time required for a fuel injector to load with fuel, discharge the fuel into the combustion chamber and then return to its original position to start the cycle over again. Cycle time is typically short for fuel injectors. For example, injectors used in a direct injection system can obtain a cycle time of 0.01 seconds. That equates to the injectors being able to load with fuel, discharge the fuel into the combustion chamber, and then prepare to reload for a subsequent cycle 100 times in a single second. While this cycle time seems very short, it is often desirable to reduce this time even further when possible.

Moreover, repeatability and precision in beginning and ending of pump stroke cycles can be important in optimizing the performance of the engine under varying operating conditions. While the cycle time may be reduced by providing stronger springs for returning the reciprocating assembly to the initial position, such springs have the adverse effect of opposing forces exerted on the reciprocating assembly by energization of the solenoid. Such forces must therefore be overcome by correspondingly increased forces

created during energization of the solenoid. At some point, however, increased current levels required for such forces become undesirable due to the limits of the electrical components, and additional heating produced by electrical losses.

5   There is a need, therefore, for an improved technique for pumping fluids in a linearly reciprocating fluid pump. There is a particular need for an improved technique for providing rapid cycle times in fluid pumps, such as fuel pumps without substantially increasing the forces and current demands of electrical driving components.

10   **SUMMARY OF THE INVENTION**

The present invention provides a novel technique for pumping fluids in a reciprocating pump arrangement designed to respond to these needs. The technique is particularly well suited for use in fuel delivery systems, such as in chamber fuel injection. However, the technique is in no way limited to such applications, and may be employed in a

15   wide range of technical fields. The pumping drive system offers significant advantages over known arrangements, including a reduction in cycle times and so forth.

The technique is based upon a drive system employing at least one permanent magnet and at least one coil assembly. The coil assembly is energized cyclically by a

20   reciprocating circuit to produce reciprocating motion of a drive member, which may be coupled directly to the coil. The drive member may extend into a pumping section, and cause variations in fluid pressure by intrusion into and withdrawal from the pumping section during its reciprocal movement. Valves, such as check valves, within the pumping section are actuated by the variations in pressure, permitting fluid to be drawn into the

25   pumping section and expressed therefrom.

More specifically, the drive section has a reciprocating coil assembly to which alternating polarity control signals are applied by a reciprocating circuit. A permanent magnet structure of the drive section creates a magnetic flux field which interacts with an

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electromagnetic field produced during application of the control signals to the coil. Depending upon the polarity of the control signals applied to the coil, the coil is driven in one of two directions of movement. The reciprocating circuit employs a storage capacitor and several switches to capture the energy of the reciprocating coil as the pump is driven

5 downwardly. The charge is recycled as the capacitor dissipates, thereby reversing the polarity of the current through the coil and driving the coil assembly upwardly to its initial position. A drive member transfers movement of the coil to a pump element which reciprocates with the coil to draw fluid into a pump chamber and expel the fluid during each pump cycle.

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BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

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Figure 1 is a diagrammatical representation of a series of fluid pump assemblies applied to inject fuel into an internal combustion engine;

Figure 2 is a partial sectional view of an exemplary pump in accordance with

20 aspects of the present technique for use in displacing fluid under pressure, such as for fuel injection into a chamber of an internal combustion engine as shown in Figure 1;

Figure 3 is a partial sectional view of the pump illustrated in Figure 2 energized during a pumping phase of operation;

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Figure 4 is a circuit diagram illustrating a reciprocating circuit and current flow in accordance with the present invention;

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Figure 5 is an exemplary embodiment of the reciprocating circuit illustrated in figure 4; and

Figure 6 is a current waveform corresponding to the reciprocating circuit illustrated in Figures 4 and 5.

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DETAILED DESCRIPTION OF SPECIFIC EMBODIMENTS

Turning now to the drawings and referring first to Figure 1, a fuel injection system 10 is illustrated diagrammatically, including a series of pumps for displacing fuel under

10   pressure in an internal combustion engine 12. While the fluid pumps of the present technique may be employed in a wide variety of settings, they are particularly well suited to fuel injection systems in which relatively small quantities of fuel are pressurized cyclically to inject the fuel into combustion chambers of an engine as a function of the engine demands. The pumps may be employed with individual combustion chambers as in the

15   illustrated embodiment, or may be associated in various ways to pressurize quantities of fuel, as in a fuel rail, feed manifold, and so forth. Even more generally, the present pumping technique may be employed in settings other than fuel injection, such as for displacing fluids under pressure in response to electrical control signals used to energize coils of a drive assembly, as described below.

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In the embodiment shown in Figure 1, the fuel injection system 10 includes a fuel reservoir 14, such as a tank for containing a reserve of liquid fuel. A first pump 16 draws the fuel from the reservoir through a first fuel line 15a, and delivers the fuel through a second fuel line 15b to a separator 18. While the system may function adequately without a

25   separator 18, in the illustrated embodiment, separator 18 serves to insure that the fuel injection system downstream receives liquid fuel, as opposed to mixed phase fuel. A second pump 20 draws the liquid fuel from separator 18 through a third fuel line 15c and delivers the fuel, through a fourth fuel line 15d and further through a cooler 22, to a feed or

inlet manifold 24 through a fifth fuel line 15e. Cooler 22 may be any suitable type of fluid cooler, including both air and liquid heater exchangers, radiators, and the like.

5   Fuel from the feed manifold 24 is available for injection into combustion chambers of engine 12, as described more fully below. A return manifold 26 is provided for recirculating fluid not injected into the combustion chambers of the engine. In the illustrated embodiment a pressure regulating valve 28 is coupled to the return manifold line 26 through a sixth fuel line 15f and is used for maintaining a desired pressure within the return manifold 26. Fluid returned via the pressure regulating valve 28 is recirculated into

10   the separator 18 through a seventh fuel line 15g where the fuel collects in liquid phase as illustrated at reference numeral 30. Gaseous phase components of the fuel, designated by referenced numeral 32 in Figure 1, may rise from the fuel surface and, depending upon the level of liquid fuel within the separator, may be allowed to escape via a float valve 34. The float valve 34 consists of a float that operates a ventilation valve coupled to a ventilation

15   line 36. The ventilation line 36 is provided for permitting the escape of gaseous components, such as for repressurization, recirculation, and so forth. The float rides on the liquid fuel 30 in the separator 18 and regulates the ventilation valve based on the level of the liquid fuel 30 and the presence of vapor in the separator 18.

20   Engine 12 includes a series of cylinders or combustion chambers 38 for driving an output shaft (not shown) in rotation. As will be appreciated by those skilled in the art, depending upon the engine design, pistons (not shown) are driven in a reciprocating fashion within each combustion chamber in response to ignition of fuel within the combustion chamber. The stroke of the piston within the chamber will permit fresh air for subsequent

25   combustion cycles to be admitted into the chamber, while scavenging combustion products from the chamber. While the present embodiment employs a straightforward two-stroke engine design, the pumps in accordance with the present technique may be adapted for a wide variety of applications and engine designs, including other than two-stroke engines and cycles.

In the illustrated embodiment, a reciprocating pump 40 is associated with each combustion chamber 38, drawing pressurized fuel from the feed manifold 24, and further pressurizing the fuel for injection into the respective combustion chamber 38. A nozzle 42

5   is provided for atomizing the pressurized fuel downstream of each reciprocating pump 40. While the present technique is not intended to be limited to any particular injection system or injection scheme, in the illustrated embodiment, a pressure pulse created in the liquid fuel forces a fuel spray 43 to be formed at the mouth or outlet of the nozzle 42, for direct, in-cylinder injection. The operation of reciprocating pumps 40 is controlled by an injection

10   controller 44. Injection controller 44, which will typically include a programmed microprocessor or other digital processing circuitry and memory for storing a routine employed in providing control signals to the pumps, applies energizing signals to the pumps to cause their reciprocation in any one of a wide variety of manners as described more fully below.

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An exemplary reciprocating pump assembly, such as for use in a fuel injection system of the type illustrated in Figure 1, is shown in Figures 2 and 3. Specifically, Figure 2 illustrates a pump and nozzle assembly 100 which incorporates a pump driven in accordance with the present techniques. Assembly 100 essentially comprises a drive

20   section 102 and a pump section 104. The drive section 102 is designed to cause reciprocating pumping action within the pump section 104 in response to application of reversed polarity control signals applied to an actuating coil of the drive section as described in greater detail below. The characteristics of the output of the pump section 104 may thus be manipulated by altering the waveform of the alternated polarity signal applied

25   to the drive section 102. In the presently contemplated embodiment, the pump and nozzle assembly 100 illustrated in Figure 2 is particularly well suited for application in an internal combustion engine, as illustrated in Figure 1. Moreover, in the embodiment illustrated in Figure 2, a nozzle assembly is installed directly at an outlet of the pump section 104, such that the pump 40 and the nozzle 42 of Figure 1 are incorporated into a single assembly 100.

As indicated above, in appropriate applications, the pump 40 may be separated from the nozzle 42, such as for application of fluid under pressure to a manifold, fuel rail, or other downstream component.

5   As illustrated in Figure 2, drive section 102 includes a housing 106 designed to receive and support the drive section 102 during operation as well as to seal the components within the housing 106. The drive section 102 further includes at least one permanent magnet 108, and in the preferred embodiment illustrated, a pair of permanent magnets 108 and 110. The permanent magnets 108 and 110 are separated from one another and disposed

10   adjacent to a central core 112 made of a material which is capable of conducting magnetic flux, such as a ferromagnetic material. A coil bobbin 114 is disposed about permanent magnets 108 and 110 and core 112. While magnets 108 and 110, and core 112 are fixedly supported within housing 106, bobbin 114 is free to slide longitudinally with respect to these components. That is, bobbin 114 is centered around core 112, and may slide with

15   respect to the core upwardly and downwardly in the orientation shown in Figure 2. A coil 116 is wound within bobbin 114 and free ends of the coil are coupled to leads L for receiving energizing control signals, such as from an injection controller 44, as illustrated in Figure 1 and discussed further with reference to Figure 4. Bobbin 114 further includes an extension 118 which protrudes from the region of the bobbin 114 in which the coil 116 is

20   installed for driving the pump section 104, as described below. Although one such extension is illustrated in Figure 2, it should be understood that the bobbin 114 may comprise a series of extensions arranged circumferentially around the bobbin 114. Finally, drive section 102 includes a support or partition 120 which aids in supporting the permanent magnets 108 and 110 and the central core 112, and in separating the drive section 102 from

25   the pump section 104. It should be noted, however, that in the illustrated embodiment, the inner volume of the drive section 102, including the volume in which the coil 116 is disposed, may be flooded with fluid during operation, such as for cooling purposes.

A drive member 122 is secured to bobbin 114 via extension 118. In the illustrated embodiment, drive member 122 forms a generally cup-shaped plate having a central aperture for the passage of fluid. The cup shape of the drive member 122 aids in centering a plunger 124 which is disposed within a concave portion of the drive member 122. Plunger 124 preferably has a longitudinal central opening or aperture 126 extending from its base to a head region 128 designed to contact and bear against drive member 122. A biasing spring 130 is compressed between the head region 128 and a lower component of the pump section 104 to maintain the plunger 124, the drive member 122, and bobbin 114 and coil 116 in an upward or biased position. As will be appreciated by those skilled in the art, plunger 124, drive member 122, extension 118, bobbin 114, and coil 116 thus form a reciprocating assembly which is driven in an oscillating motion during operation of the device as described more fully below.

The drive section 102 and pump section 104 are designed to interface with one another, preferably to permit separate manufacturing and installation of these components as subassemblies and to permit their servicing, as needed. In the illustrated embodiment, housing 106 of drive section 102 terminates in a skirt 132 which is secured about a peripheral wall 134 of pump section 104. The drive and pump sections 102 and 104 are preferably sealed, such as via a soft seal 136. Alternatively, these housings may be interfaced via threaded engagement, or any other suitable technique.

Pump section 104 forms a central aperture 138 designed to receive plunger 124. Aperture 138 also serves to guide the plunger in its reciprocating motion during operation of the device. An annular recess 140 surrounds aperture 138 and receives biasing spring 130, maintaining the biasing spring 130 in a centralized position to further aid in guiding plunger 124. In the illustrated embodiment, head region 128 includes a peripheral groove or recess 142 which receives biasing spring 130 at an end opposite recess 140.

A valve member 144 is positioned in pump section 104 below plunger 124. In the illustrated embodiment, valve member 144 forms a separable extension of plunger 124 during operation, but is spaced from plunger 124 by a gap 146 when plunger 124 is retracted as illustrated in Figure 2. Gap 146 is formed by limiting the upward movement of

5   valve member 144, such as by a restriction in the peripheral wall defining aperture 138. Grooves (not shown) may be provided at this location to allow for the flow of fluid around valve member 144 when the plunger is advanced to its retracted position. As described more fully below, gap 146 permits the entire reciprocating assembly, including plunger 124, to gain momentum during a pumping stroke before contacting valve member 144 to

10   compress and expel fluid from the pump section.

Valve member 144 is positioned within a pump chamber 148. Pump chamber 148 receives fluid from an inlet 150. Inlet 150 thus includes inlet passage 152 through which fluid, such as pressurized fuel, is introduced into the pump chamber 148. A check valve

15   assembly, indicated generally at reference numeral 154, is provided between inlet passage 152 and pump chamber 148, and is closed by the pressure created within pump chamber 148 during a pumping stroke of the device. In the illustrated embodiment, a fluid passage 156 is provided between inlet passage 152 and the volume within which the drive section 102 components are disposed. Fluid passage 156 may permit the free flow of fluid into the

20   drive section 102, to maintain that the drive section components bathed in fluid. A fluid outlet (not shown) may similarly be in fluid communication with the internal volume of the drive section 102, to permit the recirculation of fluid from the drive section 102. Valve member 144 is maintained in a biased position toward gap 146 by a biasing spring 158. In the illustrated embodiment, biasing spring 158 is compressed between an upper portion of

25   the valve member 144 and a retaining ring 160.

When the pump defined by the components described above is employed for direct fuel injection, as one exemplary utilization, a nozzle assembly 162 may be incorporated directly into a lower portion of the pump assembly 104. As shown in Figure 2, an

exemplary nozzle assembly 162 includes a nozzle body 164 which is sealingly fitted to the

pump section 104. A poppet 166 is positioned within a central aperture formed in the valve

body, and is sealed against the valve body in a retracted position. At an upper end of poppet

166, a retaining member 168 is provided. Retaining member 168 contacts a biasing spring

5   170 which is compressed between the nozzle body 164 and the retaining member 168 to

maintain the poppet 166 in a biased, sealed position within the nozzle body 164. Fluid is

free to pass from pump chamber 148 into the region surrounding the retaining member 168

and spring 170. This fluid is further permitted to enter into passages 172 formed in the

nozzle body 164 around poppet 166. An elongated annular flow path 174 extends from

10   passages 172 to the sealed end of the poppet 166. As will be appreciated by those skilled in

the art, other components may be incorporated into the drive section 102, the pump section

104, or the nozzle assembly 162. For example, where desired, an outlet check valve may be

positioned at the exit of pump chamber 148 to isolate a downstream region from the pump

chamber.

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Figure 3 illustrates the pump and nozzle assembly of Figure 2 in an actuated

position. As shown in Figure 3, upon application of energizing current to the coil 116, the

coil 116, bobbin 114, extension 118, and drive member 122 are displaced downwardly.

This downward displacement is the result of interaction between the electromagnetic field

20   surrounding coil 116 by application of the energizing current thereto, and the magnetic field

present by virtue of permanent magnets 108 and 110. In the preferred embodiment, this

magnetic field is reinforced and channeled by core 112. As drive member 122 is forced

downwardly by interaction of these fields, it contacts plunger 124 to force the plunger

downwardly against the resistance of spring 130. During an initial phase of this

25   displacement, plunger 142 is free to extend into pump chamber 148 without contact with

valve member 144, by virtue of gap 146 (see Figure 2). Plunger 142 thus gains momentum,

and eventually contacts the upper surface of valve member 144. The lower surface of

plunger 124 seats against and seals with the upper surface of valve member 144, to prevent

flow of fluid upwardly through passage 126 of the plunger 142, or between the plunger 142

and the aperture 138 of the pump section 104. Further downward movement of the plunger 142 and valve member 144 begin to compress fluid within pump chamber 148, closing inlet check valve 154.

5   Still further movement of the plunger 142 and the valve member 144 produces a pressure surge or spike which is transmitted downstream, such as to nozzle assembly 162. In the illustrated embodiment, this pressure surge forces poppet 166 to unseat from the nozzle body 164, moving downwardly with respect to the nozzle body 164 by a compression of spring 170 between retainer 168 and the nozzle body 164. Fluid 176, such

10   as fuel, is thus sprayed or released from the nozzle 162, such as directly into a combustion chamber of an internal combustion engine as described above with reference to Figure 1.

           As will be appreciated by those skilled in the art, upon reversal of the polarity of the drive or control signal applied to coil 116 through the leads L, an electromagnetic field

15   surrounding the coil 116 will reverse in orientation, causing an oppositely oriented force to be exerted on the coil 116 by virtue of interaction between this field and the magnetic field produced by magnets 108 and 110. This force will thus drive the coil 116, and other components of the reciprocating assembly back toward their original position (shown in Figure 2). In the illustrated embodiment, as drive member 122 is driven upwardly back

20   towards the position illustrated in Figure 2, spring 130 urges plunger 128 upwardly towards its original position, and spring 158 similarly urges valve member 144 back towards its original position. Gap 126 is reestablished as illustrated in Figure 2, and a new pumping cycle may begin. Where a nozzle 162 such as that shown in Figures 2 and 3 is provided, the nozzle 162 is similarly closed by the force of spring 170. In this case, as well as where no

25   such nozzle is provided, or where an outlet check valve is provided at the exit of pump chamber 148, pressure is reduced within pump chamber 148 to permit inlet check valve 154 to reopen for introduction of fluid for a subsequent pumping cycle.

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By appropriately configuring drive signals applied to coil 116 through the leads L, the device of the present invention may be driven in a wide variety of manners. Figure 4 shows a basic circuit in accordance with the present invention. The circuit 200 provides a means for driving the electro-mechanical solenoid, used here in a fuel injector, which provides for an accelerated reciprocal motion of the drive member 122 illustrated in Figures 2 and 3. The voltage source 202 is used to provide the current flow to the coil 116 through leads L illustrated in Figures 2 and 3. Also coupled to the coil 116 is a series of switches 206, 208, and 210. The switches 206, 208, and 210 are arranged to allow a capacitor 212 to store voltage to provide a reverse current through the circuit which will facilitate a faster reciprocal motion of the drive member 122 (shown in Figures 2 and 3), as discussed below. Initially, the first switch 206 is closed and the second and third switches 208 and 210 are open. When voltage is applied by the source 202, a current flows in the path indicated by current path 214. Because the first switch 206 is closed, it provides a path to ground and thus the current 214 will flow from the voltage source 202 through the coil 116 through the closed switch 206 and to ground. This actuates the coil 116, converting the electrical energy produced by the voltage source 202 into a linear motion of the drive member 122 which operates the fuel injection system, as described with reference to Figures 2 and 3.

Next, the first switch 206 is opened thereby producing a voltage across the coil 116. At this time, the second switch 208 is closed. The current flows from the voltage source 202 as indicated by current path 216. The current 216 flows from the voltage source 202 through the coil 116, through the second switch 208 and through the capacitor 212. At this time, the voltage which was stored in the coil 116 will be transferred and stored in the capacitor 212. Depending on the energy stored in the coil 116 at the time the second switch 208 is closed, and depending upon size of the capacitor 212, the voltage magnitude in the capacitor 212 will vary. Once the voltage of the capacitor 212 reaches a predetermined voltage, the second switch 208 is opened and the third switch 210 is closed. This situation will be triggered when the voltage stored in the capacitor 212 becomes higher than the voltage produced by the source 202. The current now flows through the circuit as indicated

by flow path 218. The current 218 flows from the capacitor 212 through the third switch 210 and back through the coil 116. This reverse current will push the drive member 122 back to its original position as indicated in Figure 2.

5   By using a reverse current 218 to provide reciprocal motion of the drive member 122 in accordance with the embodiment described herein, several advantages over prior electro-mechanical solenoid based systems, such as fuel injectors, may be achieved. First, as previously discussed and as will be discussed with reference to Figure 6, the cycle time for fuel injection may be reduced. Second, because the system is recycling the energy by 10   storing energy from the coil 116 in a capacitor 212 and then recycling that energy to produce the reciprocal motion of the drive member 122, the power consumption of the injection system may be reduced. Third, there is a reduction in the power dissipation in the first switch 206.

15   Figure 5 illustrates one specific embodiment of a circuit incorporating the present technique. It should be noted however that any suitable substitutes for the particular elements shown in Figure 5 may be used. Figure 5 illustrates a voltage source 302 which may be a 55 volt source. The voltage source 302 is coupled to one lead of the coil 116. The second lead of the coil 116 is coupled to the switches 306, 308, and 310. The first switch in 20   the embodiment illustrated in Figure 5 is an n-channel MOSFET 306. The drain of the MOSFET 306 is coupled to the second lead of the coil 116. The source of the MOSFET 306 is coupled to ground through a resistor 312. The gate of the MOSFET 306 is coupled to a micro-controller 314 as discussed in Figure 1 with reference to injection controller 44.

25   As discussed with reference to Figure 4, initially, the first switch 306 is closed and thus current flows from the voltage source 302 through the coil 116, through the MOSFET 306, and to ground. The micro-controller 314 will then turn the MOSFET 306 off thereby opening the gate and facilitating the storage of energy within the coil 116. In this particular embodiment, the second switch is illustrated as a diode 308. In this configuration, the

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current will initially flow through the diode 308 once the coil 116 builds a charge of over 0.7 volts. One advantage of using a diode 308 as a second switch is that the current will automatically flow through the diode 308 once the coil 116 reaches a certain threshold voltage above the voltage of the capacitor 316. Here, the voltage in the coil 116 only needs

5   to be 0.7 volts above the voltage in the capacitor 316 to activate the switch. By having an automatic activation, switch 308 does not need to be coupled to a micro-controller. This may reduce the cost of the circuit and the complexity of the design. However, it should be evident that any configuration may be used such that the switch closes when the voltage in the coil 116 reaches some greater threshold above the voltage in the capacitor 316.

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Energy is stored in the capacitor 316 until such time that micro-controller 318 closes the third switch 310. At this point, the voltage stored in the capacitor 316 will be driven back to the coil 116 thereby facilitating the reciprocating motion of the drive member 122 (shown in Figures 2 and 3) at an increased speed. Here, the third switch 310 is constructed

15   using diodes 320 and 322, resistors 324, 326 and 328, and transistor 330. However, it should be evident again that any preferred switching circuit may be used for the switch 310.

Figure 6 illustrates a current waveform in accordance with the embodiment illustrated in Figures 4 and 5. The typical cycle time for an injection cycle is greater than

20   10ms. The present embodiment however, enables an injection time of 1-7 ms as further discussed below. A waveform 400 is illustrated over time in Figure 6. The first segment 402 of the waveform 400 illustrates the fuel injection event corresponding to current path 214 in Figure 4. The cycle time for the fuel injection event according to the present embodiment is generally less than 3.5 ms. The second segment 404 of the curve 400

25   illustrates the capacitor charging as the energy from the fuel injector coil is dissipated into the capacitor, as indicated by current path 216 in Figure 4. There may be some amount of time 406 along the curve between the time that the capacitor is charging 404 and when the capacitor is discharging through the fuel injector in a reverse direction as illustrated by curve segment 408. The time it takes for the capacitor to charge from the power dissipation

from the coil and for the capacitor to discharge back to the coil to enable the reciprocal motion of the drive member may vary depending on the engine capabilities and the speed of the motor. In the present embodiment, however the cycle time may be less than 3.5 ms.

5   While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of

10   the invention as defined by the following appended claims.